An Accurate Readout Circuit for Sensors Based on Thermopiles/Thermocouples

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I. INTRODUCTION

Thermopiles and thermocouples are commonly applied in a very wide range of applications, from contactless temperature measurement, infrared gas-absorption measurement [1], climate control [2] to medical equipment and home appliances.

When a conducting material is subject to a temperature gradience, the thermoelectric effect, or Seebeck effect, will generate a voltage difference between the hot and the cold end. Since this effect is material dependent, if two different types of material is connected at one end (for instance at cold end) and open at the other end (for instance at hot end). We will see a small voltage difference at the open end. A thermocouple is based on this effect to generate a voltage difference across the output terminals proportional to the temperature difference between the hot junction and the cold junction of the sensor. This voltage is very small, generally in the range of a few µV/ºC. So in order to have a detectable output voltage, the temperature difference should be kept high. However there are special circumstances that the temperature difference can not be made large, then the use of thermopiles become inevitable. A thermopile is a large number of serially connected thermocouples. Since the output voltage is the sum of each individual thermocouple output voltage, the total output voltage is then amplified back to a detectable level. However the total output resistance of such a sensor can be very large, depending on the materials and the number of serially connected thermocouples, up to tens of kΩ or even larger [3].

In this paper we propose an interface system to measure the small output signal of a thermocouple/ thermopile sensor, with source resistance under 10 kΩ and an maximum output voltage less than 10 mV.

In section II, an overview of the complete system is introduced. Section III will discuss in detail the systematic design for a high overall system accuracy. Then the implementation and the measurement results will be given in section IV.

The presented design is a subsystem of a novel multi-functional sensor interface system called Universal Sensor Interface [4], where different types of sensors can be interfaced with a single chip by simply configuring the chip in one of the many operation modes.

II. SYSTEM OVERVIEW

The measurement system consists of a front-end amplifier, a voltage-to-time converter, control logics and frequency divider. (See Figure 1) The output of the system is then taken by a microcontroller for data record and analysis.

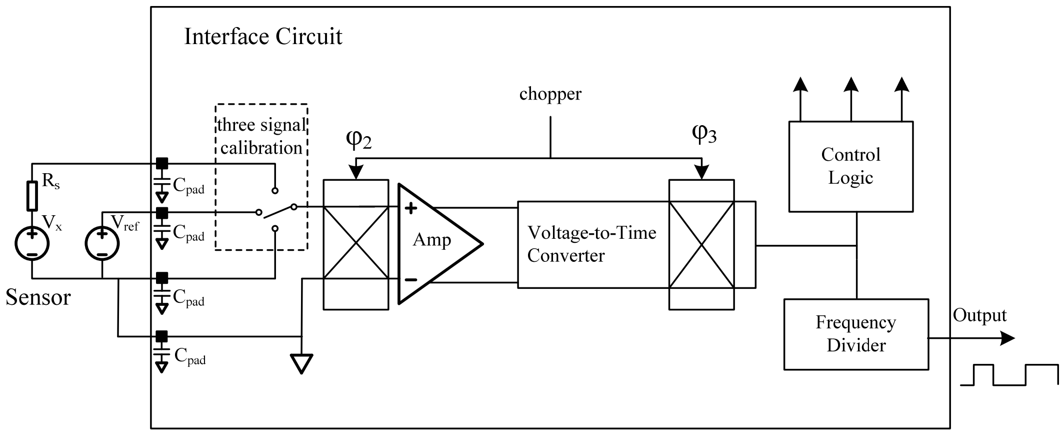

Figure 1. System Overview

The front-end amplifier is designed to amplify the input signal to an appropriate level for the voltage-to-time converter stage. The large amplification factor of 51 makes the voltage noise from latter stages insignificant. Chopper switches in front of this amplifier converts the DC voltage from the sensor into an AC square ware signal. Therefore the offset as well as the 1/f noise from the amplifier can be seperated in the frequency domain, thus be significantly reduced.

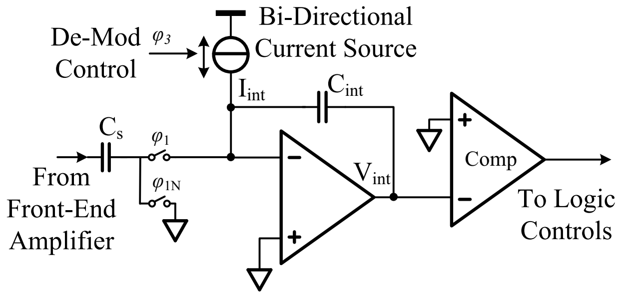

Figure 2. Voltage-to-Time Converter

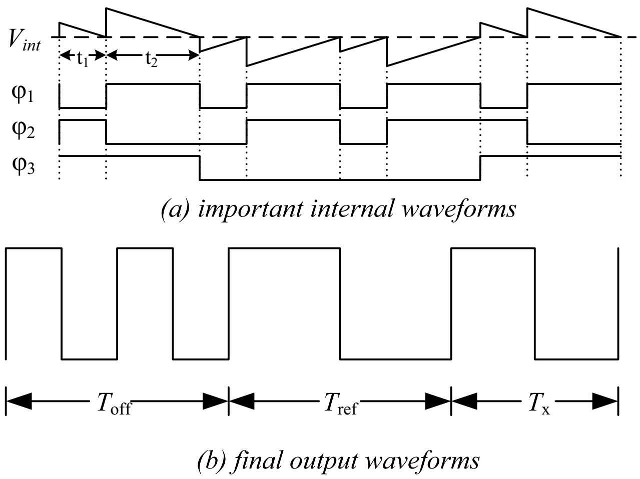

Figure 3. Important Waveforms

The output voltage of the front-end amplifier is then amplified again by capacitors C_s and C_{int} into a voltage jump at V_{int}. Meanwhile a constant current source will start to discharge the capacitor C_{int} in a way that counteracts the voltage change at V_{int}. When the voltage jump by the front-end amplifier is fully compensated by the current source, the comparator will flip into another state and consequently trigger the system into the next sampling operartion.

In order to have a better supression for low frequency interference in the signal chain, a more complex modulation scheme ("+,-,-,+" instead of "+,-,+,-" [5]) has been applied. This in turn requires an extra phase t_1 in the conversion (See Figure 3-a).

Therefore a square-wave signal, of which the period is proportional to the input signal level, is generated at the output of the comparator. This period-modulated signal is then divided as the output signal (Figure 3-b). Usually a microcontroller with a counter/timer unit converts the period length into a number of counts. This number is then processed locally or transferred to a PC or other devices for the further storage and/or analysis.

III. Design for a High Overall Signal-to-Noise Ratio

In order to achieve a high measurement accuracy for very small voltage level present in the thermocouple and/or thermopiles applications, design optimazation of all levels should be taken into account.

A. Oversampling

Temperature measurements are usually slow procedures, however with fast electronics it is possible to trade extra speed for a higher accuracy. In this system the sampling frequency is in the order of tens of kHz. This is much faster than the input signal bandwidth. For example, the specifications of a commercially available thermopile [6] shows a thermal time constant of 20 ms. Therefore we have a system with a very high over sampling ratio (OSR). This high OSR can average the in-band noise in a much larger frequency range, so that the resulted in-band noise level can be more than one order smaller. The frequency divider at the output acts as both a low pass filter and a decimation stage, which filters out all the high frequency noise and converts the signal back to the Nyquist rate.

B. Auto-Calibration

After each complete cycle of an input voltage measurement, there will be an additional offset measurement and a reference voltage measurement to enable three-signal calibration algorithm [7]. The measurand V_x is found as:

$$V_x = \frac{N_x - N_{off}}{N_{ref} - N_{off}} \cdot V_{ref} \qquad (1)$$

where N stands for the counted time period of the output signal. By applying equations (1), all the system level additive and multiplicative errors can be eliminated. Because the three measurements are performed in different time intervals, some residual errors can still remain. But these are only of the second order. The final output waveform is shown in Figure 3(b). The time intervals Toff, Tref and Tx correspond to the measurement results of the offset voltage, the reference voltage and the thermopile voltage, respectively.

C. Front-end Amplifier

In the proposed system an opamp in a non-inverting configuration is being used. With a high gain of the input amplifier, the noise contribution from the latter stages will be insignificant. On the other hand, when the first stage already dominates the total input-referred noise, an even larger gain factor does nothing but increasing the design difficulties of the amplifier. Hence in our design, a voltage gain factor of 51 has been chosen as a practical value.

The output signal of the front-end amplifier is sampled by the voltage-to-time converter. Therefore the front-end amplifier should serve the second function as an anti-alias filter. Without this filter the wideband thermal noise of the sensor would be folded into the baseband, which could result a much larger noise level in the final output signal.

D. Offset and 1/*f* Noise

Considering the very low bandwidth of the sensor output voltage, we would expect the offset voltage and 1/f noise of the CMOS amplifiers are playing a very important role in the total error. To reduce their effects, dynamic offset cancellation techniques have been introduced to cancel all these slow-varying nonidealities.

One important consequence of introducing a chopper at the input port of the interface circuit is that, due to the very high source resistance, the RC-time constant, to set up a voltage at the input of the amplifier, is not far from the range of the sampling time. This will cause a systematic error that will decrease the performance of the system. So the minimum parasitic capacitance from the input of the amplifier to ground as well as the maximum input resistance should be taken into account. In practice, due to the large area of the pads and the large junction capacitance of the ESD protection diodes, the bonding pads at the input of the chip will introduce a large parasitic capacitance. To reduce the effect of this large capacitance, the chopper has been modified to just connect the positive input terminal of the opamp to the sensor signal or to the AC ground where the bias voltage is present instead of exchanging two input terminals. In this case there is no change of the potential at the bonding pads. So only the small input capacitance of the amplifier positive input terminal needs to be charging or discharging. Thus no risk of incomplete settlings.

E. Settling Time

Due to the requirements for the voltage-to-time converter operations, the sampling time can be as fast as 1 μs. This means that the chopper's switching time can be as small as 1 μs. The amplifier should have enough settling accuracy when the sampling phase is over. Suppose the settling accuracy should be better than 0.01 %. Since a compensated opamp is a first-order system, we have

$$1 - e^{-t/\tau} = 1 - \varepsilon \qquad (2)$$

Where $\tau = 1/2\pi f$, and f is the bandwidth of the amplifier. Suppose that t = 1 μs and ε < 0.01 %, then we find the condition that f > 1.6 MHz. For the amplifier with a gain of 51, the unity-gain bandwidth of the opamp should be 51 times higher, resulting in 81.6 MHz. In practice an opamp with a unity-gain bandwidth of 100 MHz has been used.

IV. IMPLEMENTATION AND MEASURMENT RESULTS

The circuit has been implemented in a standard 0.35 µm CMOS-A process. The test chip consumes 1.8 mA current from a 3.3 V supply and measures less than 600 µm x 570 µm (taken into account the empty area) without the bonding pads (See Figure 4). The detailed measurement result is shown in Figure 5 and 6. It has been shown that the circuit has nonlinearity below 0.05% with a source impedance of 10 kΩ and an input referred noise voltage less than 1 µV with a measurement time 150 ms (See detailed result in Figure 5).

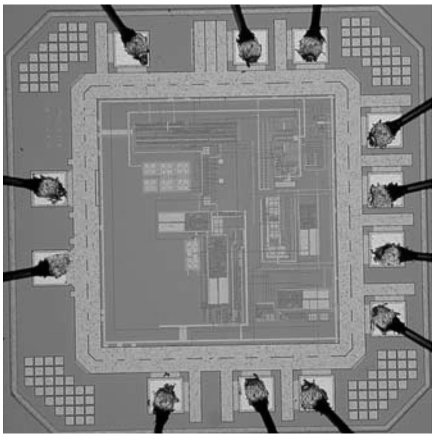

Figure 4, Chipmicrograph

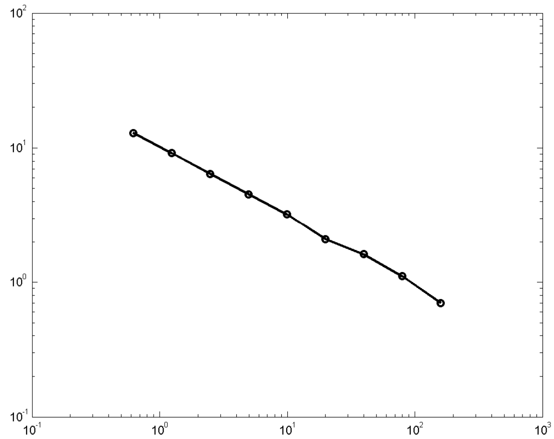

Figure 5. Resolution vs Measurement Time

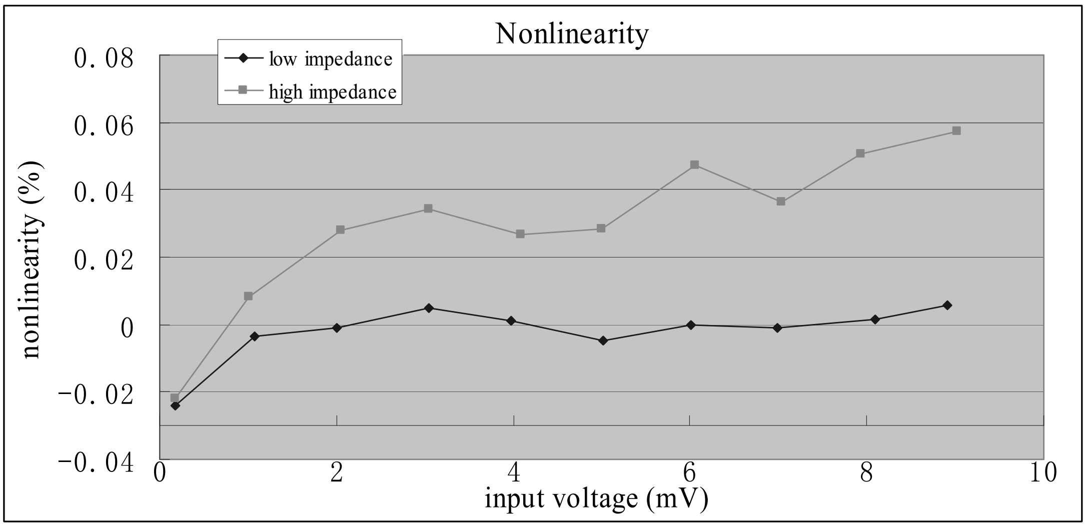

Figure 6. Nonlinearity vs input voltage. “High impedance” shows a source impedance of 10 kΩ.

V. SUMMARY

A measurement system optimized for low level voltage output sensors such as thermocouples and thermopile has been designed and implemented. From system level to transistor level, different design optimizations have been carried out to reach the highest system performance. The systematic analyses of the error sources and the techniques to reduce their effect have been presented. By applying the auto-calibration technique, a nonlinearity of below 0.06% has been achieved even with the presence of a 10 kΩ source resistance. The circuit can finish a complete measurement within 0.5 ms, which is much faster compared with the previous work. So it is suitable for a much wider range of applications. When increase the measurement time to above 150 ms, the resolution becomes better than 1 µV.

VI. ACKNOWLEDGEMENT

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